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TITLE CAN WE LEARN ABOUT THE SPIN-FLIP GIANT DIPOLE RESONANCES WITH PIONS?

DISCLAIMER

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CAN WE LEARN ABOUT THE SPIN FLIP GIANT DIPOLE RESONANCES WITH PIONS?

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ABSTRACT

Data and calculations for the $^{40}Ca(\pi^{\pm},\pi^0)$ reactions at 164 MeV are shown which indicate that pion scattering possesses a unique signature for separately identifying the 1^- and 2^- spin-isospin components of the giant dipole resonance.

INTRODUCTION

We have heard a great deal about (p,n) charge exchange. Now we come to the part of the program entitled "other reactions," which includes the $(\pi^{\pm},\pi^0)$ reactions, and later in this session the (π^-,γ) reaction. Since the theme of this conference is spin-excitations in nuclei, I was asked to talk briefly about the possibilities of the $(\pi^{\pm},\pi^0)$ reactions for study of spin excitations. I must say that at present spin aspects do not constitute the major thrust of our studies.[1] Nevertheless, there was a puzzling feature in the $^{40}Ca(\pi^{\pm},\pi^0)$ data at 164 MeV which led to an unexpected result with regard to spin excitations with pions. This will be the subject of my talk.

Most of the discussions here have dealt with spin-excitations of unnatural parity states. Of course, one can have spin-transfer $\Delta S = 1$ in the excitation of natural parity states. The surprising phenomenon in pion scattering is for 1^- states. We were led to consider $\Delta L = 1$, $\Delta S = 1$ pion excitations in attempting to understand the observed angle-dependent broadening of the giant dipole resonance (GDR) in the $^{40}Ca(\pi^{\pm},\pi^0)$ reactions. In March-April 1981 we were performing the first survey experiments on isovector giant resonances with the LAMPF π^0 spectrometer set up at the low-energy pion (LEP) channel. The $^{40}Ca(\pi^{\pm},\pi^0)$ measurements played the role of a calibration experiment. We wanted to see how well the isovector resonances stand out above the continuum and if the cross sections could be understood quantitatively. Since ^{40}Ca has a well-formed GDR at 20 MeV excitation with a width Γ = 4.5 MeV (FWHM),[2] it was important to see this resonance clearly. Fig. 1 shows the 12^0 and 3.5^0 spectra we had in the counting house during the experiment. There is a good signal to background ratio for the GDR at 12^0 and almost no trace of the GDR at 3.5^0. In the off-line analyses we binned the data into six angular bins as shown for the (π^+,π^0) reaction in Fig. 2. The data displayed in Fig. 2 were taken in two settings of the spectrometer, 0^0 and 20^0, with a total data-taking time of 16 h. With these two settings we covered the angular range 0^0 to 30^0. The 15^0 spectrum shows a nice GDR signal at the expected position for the analog of a 20 MeV state in ^{40}Ca. The observed signal at 15^0 has a width 6.6 ± 0.7 MeV for the (π^+,π^0) spectrum and 6.1 ± 0.5 MeV for the (π^-,π^0) spectrum. These values are larger than the 5.0 ± 0.2 MeV instrumental resolution and are consistent with a GDR width of 4 ± 2 MeV (FWHM). The measured angular distribution is well described by the function[3] 2.9 $J_1^2(q_\perp R)$ mb/sr where $q_\perp$ is the component of the momentum transfer $\vec{q}$ which is perpendicular to the incident beam direction.

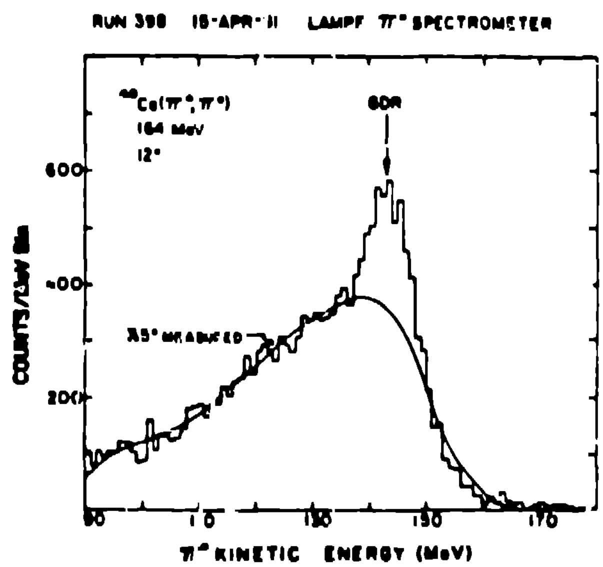

Fig. 1. One of the first spectra measured on the $^{40}Ca(\pi^+,\pi^0)$ reaction which showed that the giant dipole resonance (GDR) is strongly excited in pion single charge exchange. The arrow marks the position for a state corresponding to 20 MeV excitation in ^{40}Ca.

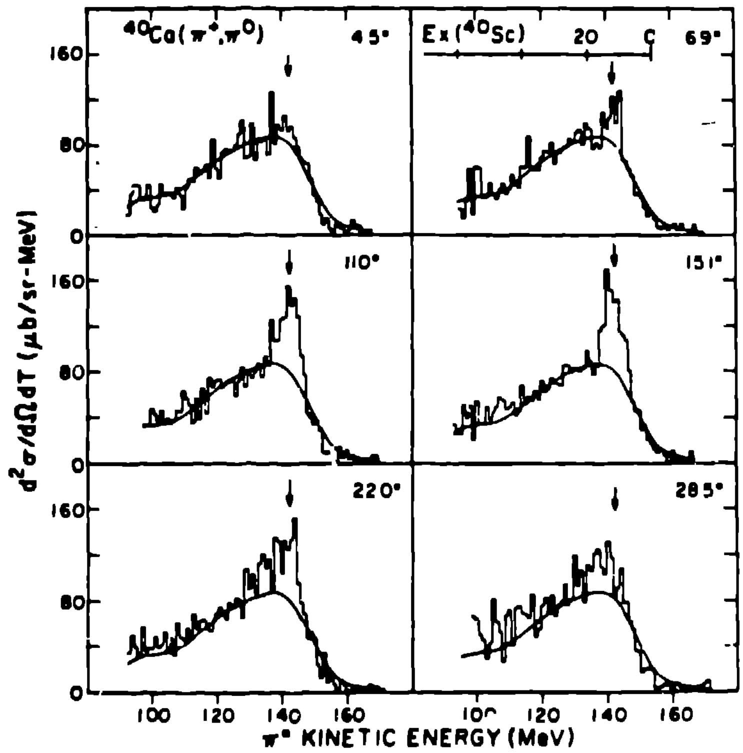

Fig. 2. The measured π^0 spectra for the $^{40}Ca(\pi^+,\pi^0)$ reaction at 164 MeV. The arrow marks the expected position of the analog of the giant dipole resonance at 20-MeV excitation in ^{40}Ca. The solid line in all panels is the smoothed, but not renormalized, 4.5^0 spectrum.

R is the pion interaction radius. A value R = 4.8 fm, deduced from the first minima of elastic π^+ and π^- scattering, gives a good fit of J_1^2 to the GDR angular distribution. The maximum value of 2.9 J_1^2 occurs at 15.4^0 with cross section 0.93 mb/sr. This value is close to what is expected[1,3] in a calculation using the Goldhaber-Teller form of the transition density normalized to exhaust the classical E1 sum rule. Thus the energy, width, cross section, and angular distribution shape for the signal we see in the $^{40}Ca(\pi^+,\pi^0)$ reaction identifies it as the analog in ^{40}Sc (at 12.34 MeV excitation) of the E1 photo-resonance observed[1] in ^{40}Ca at 20 MeV.

It is interesting to compare the (p,n) and (π^+,π^0) reactions to see how best to exploit the differences for structure studies. The ^{40}Ca(p,n) spectrum at 200 MeV and 4^0 shown in Fig. 3a was presented at an earlier session. Fig. 3b shows the 15^0 spectrum for the $^{40}Ca(\pi^+,\pi^0)$ reaction at 164 MeV. The momentum transfer is

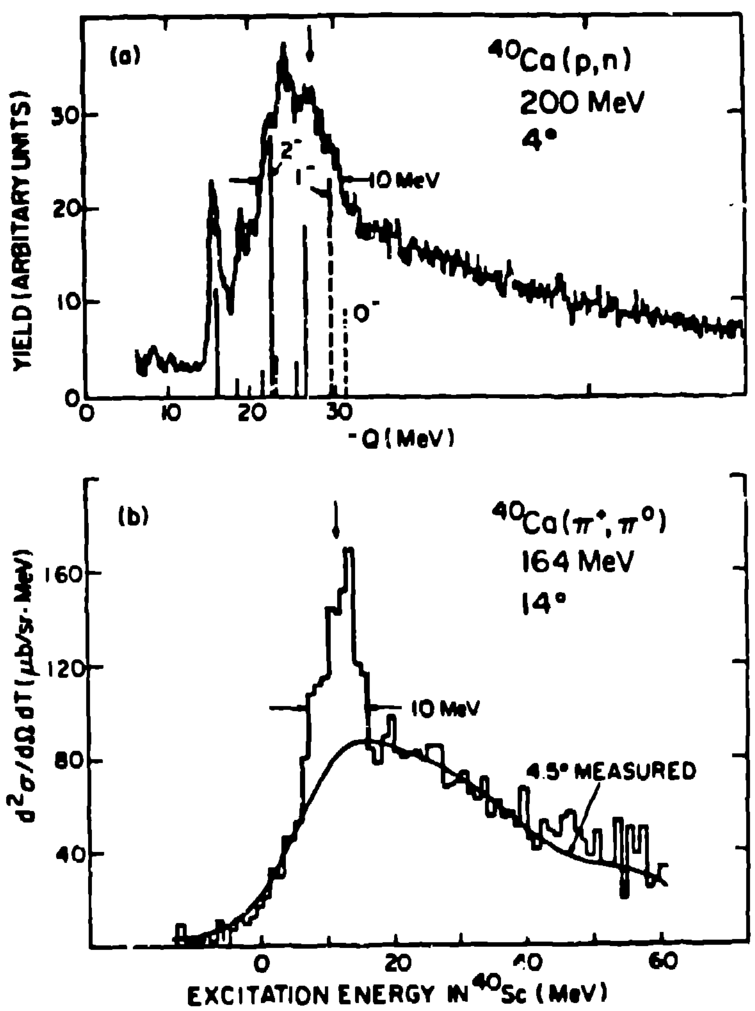

Fig. 3a. $^{40}Ca(p,n)$ data shown at this conference by K. Gaarde.[4]
3b. The π^0 spectrum for the $^{40}Ca(\pi^+,\pi^0)$ reaction at an angle where the GDR has the maximum cross section. The measured spectrum (smoothed) at 4.5^0 is shown for comparison. The arrow in both (a) and (b) marks the expected positions of the GDR at 20 MeV excitation in ^{40}Ca.

≈65 MeV/c for both spectra. The two spectra look quite similar, and one might be tempted to conclude that the two charge exchange reactions excite the same states when compared at the same q-value. From our present understanding, nothing could be further from the truth. Nearly the entire (p,n) cross section in the GDR region is being interpreted as due to $\Delta L = 1$, $\Delta S = 1$ transitions to 0^-, 1^-, 2^- states. Nearly the entire (π^+,π^0) cross section in the GDR region is being interpreted as due to $\Delta L = 1$, $\Delta S = 0$

transitions to 1^- states. The (π^+,π^0) peak is the parent state ($M_T = T = 1$) to the photo-resonance ($M_T = 0$, $T = 1$) of ^{40}Ca, whereas the (p,n) peak is of different origin. Its strength is related to the $(\vec{\sigma} \times \vec{r})_1$ operator which plays a minor role in photoabsorption. From this comparison one can see the complementary roles of pion- and nucleon-charge-exchange scattering in clarifying the full nature of the GDR.

The best resolution that we have obtained in (π^-,π^0) measurements is 2 MeV (FWHM). This still is larger than the few tenths-of-MeV for the (p,n) studies. There is, however, a nice advantage to pion charge exchange measurements. The switch in measurement from (π^+,π^0) to (π^-,π^0) is much simpler than from (p,n) to (n,p). We simply reverse the polarity of the channel magnets. This gives data such as that displayed in Fig. 4. One sees directly the shift in mass between nuclear states due to the addition of 2 units of charge, which for ^{40}Ca is 12.0 MeV. The comparison of the two spectra is useful for distinguishing resonance peaks from artifacts of the continuum. A nuclear eigenstate must shift according to the Coulomb displacement energy, whereas the continuum may differ for the two reactions due to different neutron and proton separation energies, and due to

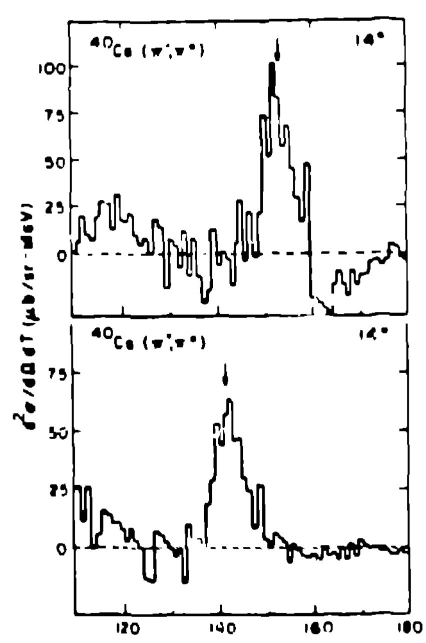

Fig. 4. The π^0 spectra at 14° after subtraction of the continuum. The arrows mark the expected position of the GDR. The peaks show the expected displacement of 12 MeV due to the difference in Coulomb energies.

Coulomb effects is suppressing the endpoint of the π^0 spectrum in the final state of the $\pi^+A \rightarrow (A-1)p\pi^0$ channel. Thus the solution of the difficult and long-standing problem of separating continuum and resonance excitation in an experimental spectrum is greatly aided by comparing the two charge-exchange spectra.

ANGLE-DEPENDENT BROADENING OF THE GDR SIGNAL

There is a puzzling feature in the $^{40}Ca(\pi^{\pm},\pi^0)$ data. The GDR signal has a smaller width in the 14^0 spectra than in the 10^0, 22^0, and 28^0 spectra. The measured width at 14^0 is consistent with an intrinsic GDR width of 4 ± 2 MeV. At the other angles,

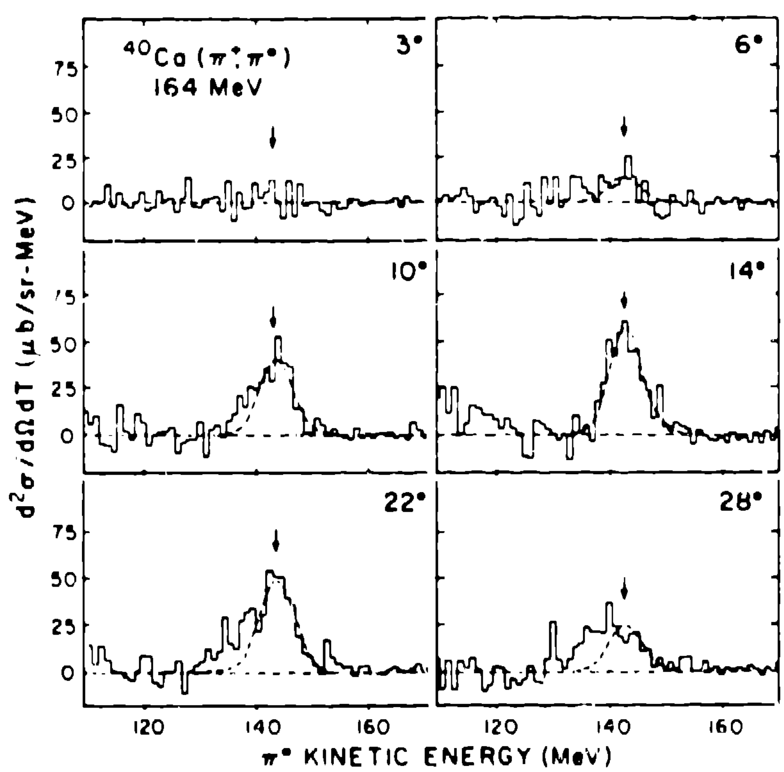

Fig. 5. The $^{40}Ca(\pi^+,\pi^0)$ spectra after subtraction of the continuum. The arrow marks the expected GDR position. The spectra at 10^0, 22^0, and 28^0 are suggestive of a second peak separated by ≈5 MeV from the main GDR peak. The 3^0 and 14^0 spectra do not show this second peak. The dashed curves are Gaussian functions with parameters held fixed at the values obtained in the fit at 14^0. (These data are from an analysis with XCUT = 0.2; the data of Fig. 2 are with XCUT = 0.1.)

one sees a broadening on the low-energy side of the GDR peak in both the (π^+,π^0) and the (π^-,π^0) data. Fig. 5 shows this effect for the (π^+,π^0) data. In view of this broadening, a further analysis of the (π^+,π^0) data was carried out. The peak structure for each angle was fitted with two Gaussian functions, keeping the main peak parameters fixed at the position and width given by the 14^0 data. The data, together with the Gaussian function for the main peak, are shown in Fig. 5. The excess counts on the low-energy side are clearly evident. The position of this subsidiary peak is 5 ± 2 MeV below the main GDR. The angular distributions of both the main peak and the excess counts are given in Fig. 6. The dashed curve is intended only to guide the eye. Although the uncertainties in the deduced cross sections are large, certain qualitative features are evident: 1) there is a minimum near 14^0; 2) the cross section rises between 14^0 and 28^0; 3) the maximum observed cross section is at 28^0 where it has a value 0.12 ± 0.06 mb/sr which is approximately 15% of the GDR cross section at 14^0. This angular distribution shape was puzzling. The $\Delta S = 0$, $\Delta L = 0$, 1, and 2 transitions are expected to peak at 0^0, 15^0, and 30^0, following closely the functions J_0^2, J_1^2, and J_2^2, respectively. The $0^+ \rightarrow 1^+$ transitions in pion scattering do not peak at 0^0 as they do for the (p,n) reaction. In the absence of more complicated effects than those treated by Siciliano and Walker,[5] transitions to unnatural parity excitations have a negligibly small cross section at 0^0. A $0^+ \rightarrow 1^+$ transition in ^{40}Ca at $T_\pi = 164$ MeV would be expected to have its first

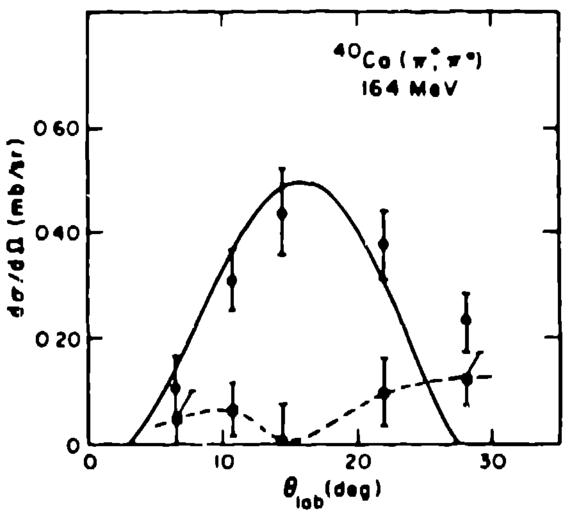

Fig. 6. The measured angular distribution for the main GDR (circles) and for the second state (squares) at ≈25 MeV excitation in ^{40}Ca. The solid curve represents the function $\beta[J_1^2(qR) - J_1^2(3^0)]$; the dashed curve is a hand-drawn line to guide the eye.

maximum near 20°. Thus we were led to examine $\Delta L = 1$, $\Delta S = 1$ transitions.

CONSEQUENCES OF SPIN-TRANSFER IN $\Delta L = 1$ EXCITATIONS WITH PIONS

The shell model calculations of Donnelly and Walker[6] show that there are two 1^- states of quite different character near 20 MeV excitation in ^{40}Ca. Fig. 7 shows the calculated excitation energies and the values of the dipole strength $D = |\int \psi_f^* \vec{r} \psi_i|^2$ and the spin-flip dipole strength $SD = |\int \psi_f^* (\vec{\sigma} \times \vec{r})_1 \psi_i|^2$ for the calculated 1^- states. The dipole strength is largely concentrated in a single state at 18.6 MeV for which D = 0.88 and SD = 0.03. The spin-flip dipole strength is largest for a state at 22.2 MeV for which D = 0.08 and SD = 0.55. The separation energy for these two states is 3.6 MeV. The lower state represents the main component of the photonuclear GDR at 20 MeV. The higher 1^- state, if expected at 23.6 MeV, is at about the right energy to be a candidate for our satellite peak. Its wave function, $0.965(d5/2^{-1}f5/2)1^-$ + (small pieces), is dominated by a

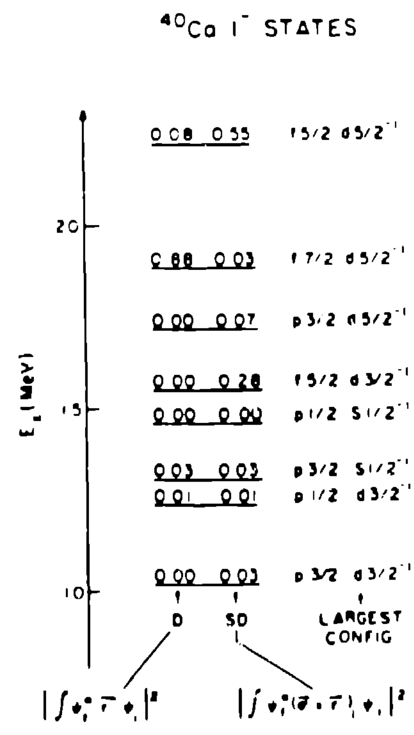

Fig. 7. The spectrum of 1^- states in a 1 $\hbar\omega$ basis calculated by Donnelly and Walker.[6]

configuration of the "spin-flip" type, i.e., $j_h = \ell + 1/2$ and $j_p = \ell - 1/2$. The lower 1^- state has three large components,

$$0.711(d5/2^{-1}f7/2) + 0.503(d3/2^{-1}f5/2) + .362(d5/2^{-1}p3/2)$$

all of which are of the "non-spin-flip" type, i.e., $j_h = \ell + 1/2$ and $j_p = \ell + 1/2$ or $j_h = \ell - 1/2$ and $j_p = \ell - 1/2$. When these two types of configurations were put into a DWIA calculation for pion inelastic scattering, it came as a surprise that the predicted angular distributions were very different. Some representative calculations by Siciliano[5] are shown in Fig. 8. The spin-flip configurations, e.g. $(d5/2^{-1}f5/2)1^-$, have angular distributions which peak at 0^0, and have the first minimum near 20^0. The non-spin-flip configurations, e.g. $(d3/2^{-1}f5/2)1^-$, have the expected J_1^2 angular distribution, with the first maximum near 15^0 and minima at 0^0 and 35^0.

Further DWIA calculations were performed in which the transition amplitudes were decomposed into amplitudes with spin-transfer values $\Delta S = 0$ and $\Delta S = 1$. These contributions add incoherently in the cross section (within the usual DWIA description). Fig. 9 shows the separate contributions for the $(d5/2^{-1}f5/2)1^-$ configuration. From this decomposition we see that the $\Delta S = 1$ amplitude is responsible for the 0^0 maximum. The $\Delta S = 0$ curve peaks at 15^0 and has minima at 0^0 and 35^0. It has the same shape as the $(d5/2^{-1}f7/2)1^-$ angular distribution in Fig. 8 which is dominated by the $\Delta S = 0$ component.

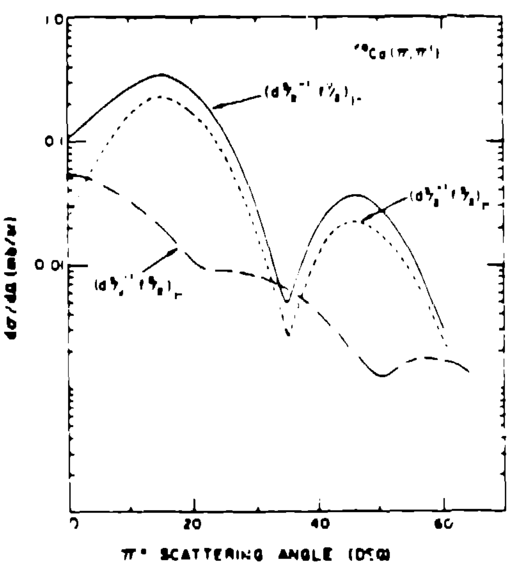

Fig. 8. DWIA calculations performed by E. R. Siciliano[5] for 1^- states excited in pion scattering at 164 MeV. The assumed p-h configurations are indicated.

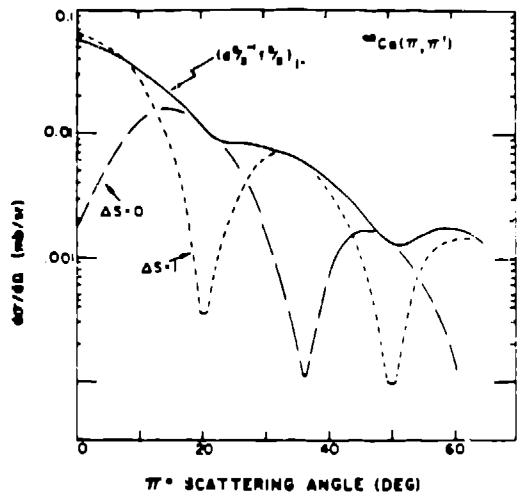

Fig. 9. DWIA calculations[5] showing the separate contributions of $\Delta S = 0$ and $\Delta S = 1$ amplitudes for a p-h configuration where $j_h = \ell + 1/2$ and $j_p = \ell - 1/2$.

These features may be understood as follows. The isovector component of the elementary $\pi - N$ scattering amplitude is well approximated at the P33 resonance by

$$f(k,k') = \alpha(k)[2\cos\theta + i\vec{\sigma}\cdot\hat{n}\,\sin\theta]\vec{\tau}\cdot\vec{t} \ .$$

The $\Delta S = 0$ transitions are induced by the scalar term ($2\cos\theta$) and the $\Delta S = 1$ transitions are induced by the spin-dependent term ($\vec{\sigma}\cdot\hat{n}$ $\sin\theta$). Thus there is a factor of four in the cross section favoring $\Delta S = 0$ to $\Delta S = 1$ transitions arising from the elementary interaction. For any configuration the relative $\Delta S = 0$ to $\Delta S = 1$ amplitudes are determined by the j-j to L-S recoupling coefficients. When the nuclear p-h excitation is of the non-spin-flip type, e.g. $(d5/2^{-1}f7/2)1^-$, the ratio of amplitudes $\Delta S = 0/\Delta S = 1$ arising from the j-j to L-S recoupling is much larger than one. Thus for these configurations the DWIA calculations show a nearly pure $\Delta S = 0$ shape. When the configuration is of the spin-flip type, e.g. $(d5/2^{-1}f5/2)1^-$, the $\Delta S = 1$ amplitude is much larger. In some cases (all the cases we investigated) it is sufficiently large to produce an absolute maximum at 0^0.

For 2^- states the situation is a little different. Angular momentum and parity conservation force $\Delta S = 1$. However, now there can be the two values $\Delta L = 1$ or 3. From the DWIA formalism one can see that the requirement $\Delta S = 1$ forces the 2^- cross section to go to zero at 0^0 for both L values. The relative amounts of $\Delta L = 1$ to $\Delta L = 3$ affects the angle at which the angular distribution peaks. Representative calculations for $(d5/2^{-1}f7/2)2^-$ and $(d5/2^{-1}f5/2)2^-$ configurations are shown in Fig. 10. They peak at 24^0 and 28^0, respectively. The non-spin-flip type configuration $(d5/2^{-1}f7/2)2^-$ gives a larger cross section by a factor of 5.3. It also has the larger $\Delta L = 1/\Delta L = 3$ amplitude ratio. It is worth noting that the $\Delta S = 1$ cross section differs dramatically for 2^- and 1^- states. The $\Delta S = 1,1^-$ cross section peaks at 0^0 and has a second maximum at 35^0 (Fig. 8). The $\Delta S = 1,2^-$ cross sections are zero at 0^0 and have their first maxima near 25^0 (Fig. 10).

To recapitulate, we see that there are three types of angular distributions involved in the excitation of 1^- and 2^- giant dipole states. The primary maxima of these angular distributions occur at 0^0, 15^0, and 25^0 and are therefore easily distinguishable in an experiment. The 1^- states have two types of angular distribution shapes characterized in the extreme by pure $\Delta S = 0$ or $\Delta S = 1$ transitions. For the p-h configurations involved in ^{40}Ca, the configurations of spin-flip type, e.g., $(d5/2^-f5/2)1^-$, give a large $\Delta S = 1$ amplitude which produces a maximum in the cross section at 0^0. If the configurations are of non-spin-flip type, as they are predominantly in the photonuclear GDR of ^{40}Ca, the $\Delta S = 0$ amplitude dominates and one gets the classical

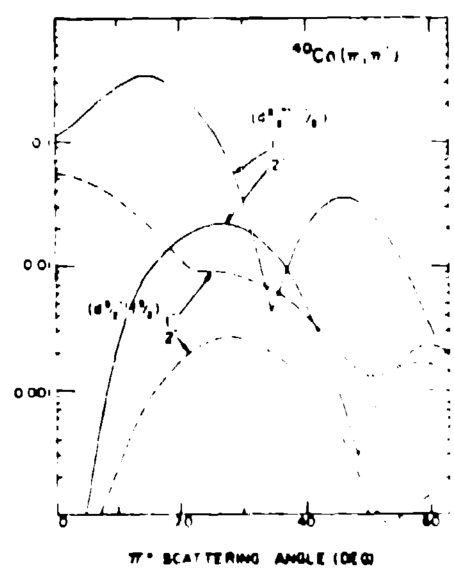

Fig. 10. DWIA calculations[5] for 1^- and 2^- states with pure h-p configurations. These configurations are the major components in the wave functions of Donnelly and Walker[6] for the relevant dipole states.

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EIKONAL TREATMENT OF SPIN-FLIP

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approaches its first zero and J_1
this occurs near 15^0. For larger
lates but drops off. These eikonal
tative agreement with the DWIA

$$\frac{d\sigma}{d\Omega}(0^-) = 0$$

$$\frac{d\sigma}{d\Omega}(1^-, \Delta S = 0) = N_1 J_1^2(x)$$

$$\frac{d\sigma}{d\Omega}(1^-, \Delta S = 1) = N_2 |\sigma\alpha J_0(x)$$

$$\frac{d\sigma}{d\Omega}(2^-, \Delta S = 1) = N_2 |\sigma\alpha J_2(x)$$

where $x = q_t R = p'R \sin\theta$ and σ
A sketch of these functions wi
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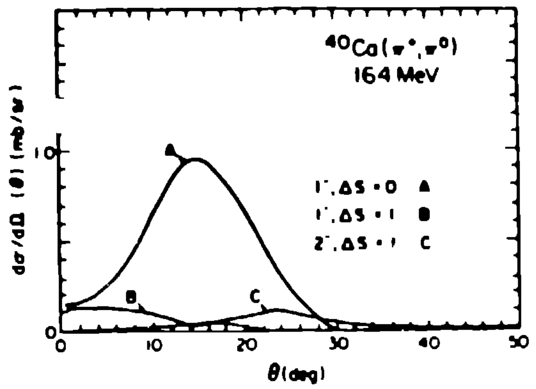

Fig. 11. A qualitative sketch of cross sections predicted by Gal[3] for giant dipole states in ^{40}Ca. The fourth member of the spin-isospin GDR multiplet has $\Delta S = 1$, $\Delta L = 1$, $J^\pi = 0^-$ but its excitation is forbidden in pion scattering by parity conservation.

Gal points out that the 0^0 peaking of the $\Delta S = 1, 1^-$ cross section depends quadratically on the πN total cross section σ. Thus, above the (3,3) resonance the $\Delta S = 1, 1^-$ cross section becomes negligible even at 0^0.

The $\Delta S = 1, 2^-$ cross section starts at zero at 0^0 and rises slowly for $\theta \lesssim 15^0$ (for ^{40}Ca). It reaches a maximum near 24^0, estimated to be 0.1 mb/sr. The second minimum is near 35^0. This shape is in qualitative agreement with DWIA calculations (Fig. 10). From the DWIA calculations one can see that in order to reach a cross section of 0.1 mb/sr for 2^- states one must have coherent p-h excitation of the non-spin flip type, e.g., $(d5/2^{-1} f7/2)2^-$. These are the same type of configurations involved in the 1^- GDR state.

COMPARISON WITH EXPERIMENT

Now that the theoretical expectations are quite explicit, we can go back and ask about the experimental verification and new measurement possibilities. First we see that if we take Gal's graph (Fig. 11) for the sum of $\Delta S = 0, 1^-$, $\Delta S = 1, 1^-$, and $\Delta S = 1, 2^-$ transitions, it is in qualitative agreement with the data (Fig. 6). In the comparison we should plot the theoretical cross section relative to the 4.5^0 values since this is how the data was analyzed. The rise in the cross section for the satellite peak beyond 15^0 would be due to 2^- states. At 0^0 the peak of the $\Delta S = 1, 1^-$ state is obscured by the $\Delta S = 0, 1$ GDR. Gal's calculations show that the two states have comparable cross sections. We used the 4.5^0 spectrum to give us the shape of the continuum at other angles. The presence of $\Delta S = 1,1^-$ components makes this procedure less accurate. The result is that we cannot for certain identify $\Delta S = 1,1^-$ states in ^{40}Ca. However, the data is consistent with the expectations for $\Delta S = 1,2^-$ states.

It may be possible to enhance the $\Delta S = 1,1^-$ states relative to the $\Delta S = 0,1^-$ states at 0^0 by lowering the beam energy. Excitation functions measured for other nuclei show that the ratio $\sigma(\Delta S = 1)/\sigma(\Delta S = 0)$ measured at constant momentum transfer is a sharp function of pion energy (for a review of this point, see Ref. 8). In the examples studied (2^- and 4^- states) a lower pion energy near 100 MeV is much more favorable for enhancing the spin-flip excitations relative to non-spin flip excitations.

The best experimental evidence for the validity of the theoretical predictions on 1^- state angular distributions comes from the very recent experimental result discussed in Ref. 8. Fig. 12 shows the measured angular distributions for π^+ and π^- inelastic scattering at 162 MeV to a known 1^- state at 4.45 MeV in ^{18}O. The curves are DWIA calculations for $\Delta S = 0$ and $\Delta S = 1$ transitions obtained from a $(p1/2^{-1}d3/2)1^-$ configuration. We see that the $\Delta S = 1$ and $\Delta S = 0$ curves are out of phase, and that the

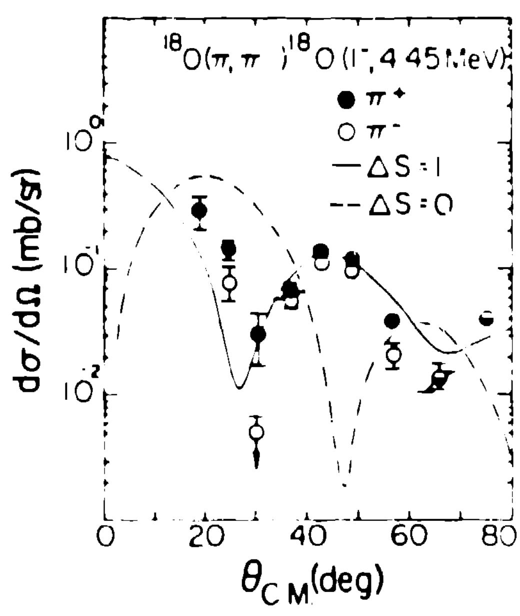

Fig. 12. Preliminary data and calculations of S. Seestrom-Morris et al.[8] on ^{18}O which give evidence that $\Delta S = 0,1^-$ and $\Delta S = 1,1^-$ excitations may have very different angular distributions in pion scattering.

data agree quite well with the $\Delta S = 1$ curve. Calculations with other p-h configurations give similar $\Delta S = 1$ and $\Delta S = 0$ curves. The data and calculations taken together indicate a nearly pure $\Delta S = 1$ excitation. Whether this is consistent with realistic shell model calculations remains to be seen. Taken at face value, these preliminary results give a first clue that $\Delta S = 1,1^-$ and $\Delta S = 0,1^-$ transitions in pion scattering might have quite different angular distribution shapes.

SUMMARY

Theoretical studies performed in June-September 1981 predicted there exist large differences in the angular distribution shapes of $\Delta S = 0,1^-$ and $\Delta S = 1,1^-$ transitions. At forward angles these two angular distributions are nearly out of phase. The $\Delta S = 1,1^-$ cross section peaks at 0^0, and the $\Delta S = 0,1^-$ cross section peaks at 15^0. The preliminary data on the $^{18}O(\pi,\pi')^{18}O(1^-,4.45$ MeV) angular distribution at 164 MeV and in the region 20^0-60^0 has a shape which looks very much like the calculations for $\Delta S = 1,1^-$ states.

For the study of spin-flip components of the GDR, the differences in angular distribution shapes between $\Delta S = 0,1^-$, $\Delta S = 1,1^-$, and $\Delta S = 1,2^-$ transitions offers a powerful method for separating these components experimentally. However, to exploit this possibility in pion charge exchange scattering requires higher π^0 resolution than 5 MeV(FWHM) and/or an enhancement of the strength of $\Delta S = 1$ transitions relative to $\Delta S = 0$ transitions at other beam energies.

It might be of interest to mention that we at Los Alamos have studied the possibilities for higher resolution. A π^0 resolution of order 0.3 MeV (FWHM) seems quite feasible for a second generation spectrometer based on the present design, with NaI detectors replacing the lead glass Cherenkov detectors.

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